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Plasma Channel Formation and Guiding During High Intensity Short Pulse Laser Plasma Experiments

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A plasma waveguide is formed during the interaction of a high power (2TW) subpicosecond pump laser pulse with a hydrogen (or helium) gas jet target. The channel is produced from displacement (or cavitation) of plasma electrons by the large ponderomotive force of the focused pump laser and the subsequent radial expulsion of plasma ions due to charge separation. Using Thomson scattering diagnostics and mode structure measurements, a trailing probe laser pulse is observed to be guided throughout the length of this channel for about 20 Rayleigh lengths - approximately equal to the propagation length of the self-guided pump laser pulse.

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PLASMA CHANNEL FORMATION AND GUIDING DURING HIGH INTENSITY SHORT PULSE LASER PLASMA EXPERIMENTS

The development of ultra-high intensity lasers [1] over the past several years has led to a number of proposed applications — in particular, x-ray laser [2, use different feference] and laser-driven electron acceleration schemes such as the Laser Wakefield Accelerator, LWFA [3]. In practical terms, these applications require long interaction distances, implying that the high intensity laser pulse must propagate for distances significantly greater than the vacuum diffraction length, which is typically only a few hundred microns if the beam is tightly focused. By increasing the length in which high laser intensity exists it should also be possible to significantly enhance the efficiency of other nonlinear phenomena [4]. Optical guiding of intense laser pulses was also proposed for the "Fast Ignitor" schemes in inertial confinement fusion experiments [13].

Guiding of laser light up to intensities of 10^{15} W/cm^2 has recently been measured in a waveguide structure created by the hydrodynamic expansion of a preformed plasma [5] as well as intensities of 10^{17} W/cm^2 in glass capillary waveguides [6]. For laser pulses above the critical power of relativistic optical guiding given by $P_{crit} = 17\ (\omega_{pe}/\omega_0)^2$ GW (where ω_{pe} is the electron plasma frequency and ω_0 is the laser frequency), self–channeling of laser pulses in plasmas has been experimentally observed [7]. This phenomenon has been the subject of extensive theoretical examination [8-11].

Self-focusing of intense laser pulses in plasmas can also be achieved by the expulsion of plasma electrons (cavitation) caused by the extreme ponderomotive force of a focused laser pulse [12, PRL on back-side-scatterd 2nd harmonics]. In this letter, experiments at the Naval Research Laboratory (NRL) will be discussed in which we observed the optical guiding of high intensity laser pulses in underdense plasmas and the creation of a plasma channel that guides subsequently injected laser pulses. The radial electrostatic force from charge separation expels the plasma ions from the electron cavitation regions. Due to their inertia, the ions continue to drift radially outward even after the passage of the laser pulse and a plasma channel is formed. Our experiments showed that a trailing probe laser pulse channeled in a structure produced by a 2.0

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TW pump laser pulse for temporal delays of up to 50 psec. The propagation distance is measured to be approximately 30 Rayleigh lengths.

These experiments were performed with the NRL table-top terwatt laser system (a Ti:Sapphire/Nd:Glass laser system using chirped pulse amplification) at a wavelength of 1.054 μm. The peak power is ~2 TW with a pulselength of typically 400 fsec and a focused peak intensity of 4 x 10^{18} W/cm^2. To reduce effects of ionization induced defocusing [14] we used a gas jet of hydrogen (H_2) which produced a maximum plasma density of $n_e \approx 10^{19}$ cm^{-3} when ionized. The plasma has a uniform region of about 2 mm in the center of the jet and a density gradient of ~0.5 mm at the edges. We measured the plasma density profile by recording the wavelength shift of stimulated Raman backscattered light at moderate laser intensities (10^{16} W/cm^2) with no channeling. Helium was also used which produced similar experimental results. A CCD camera is positioned at 90 degrees from the axis of laser propagation to image the interaction region, and a second CCD array is used to image the mode structure of the channeled pulse at the "exit" of the plasma channel.

The length of the interaction region was observed with the sidescattered Thomson emission from the pump light (using an infrared filter) imaged onto the 90° CCD camera. As the laser power was increased, the length of the emission region increased to about 2.5 mm at 2 TW (see Figure 1A). However, extended regions of self-focusing were observed for incident laser powers of 1 TW (Fig. 1B) which is significantly less than the theoretical critical power for relativistic self-focusing at these densities (~ 1.7 TW). Such guiding can not be attributed to atomic nonlinear self-focusing effects since hydrogen gas is completely ionized at a relatively low intensity (~10^{14} W/cm^2). In addition, when pre-ionizing pulses of between 1 - 10 % of the total energy were used, no qualitative change in the Thomson scattered image was observed. If we assume that the focal spot size of the laser pulse in the plasma is similar to that in vacuum, then this channeled region corresponds to a distance of 30 Rayleigh lengths. The self focusing of the pump laser is probably caused by the combined effect of relativistic self-focusing and electron cavitation which might have lower the critical power. Images of the Thomson scattered

light typically exhibited a number of separate foci during these interactions and their positions were not precisely reproducible from shot to shot. They are probably caused by envelope oscillations from the mismatch of the laser pulse spot size to that of the channel.

A pump-probe experimental arrangement was used to monitor the temporal characteristics of the high intensity laser produced plasma. Approximately 10 % of the main laser beam was extracted with a pellicle and frequency doubled to 527 nm and ~ 10 mJ with a $KD^{*}P$ crystal to form a probe beam. This probe beam was then sent through an adjustable delay line before recombining with the pump pulse in the focusing optics (an f/3 off-axis parabolic mirror). Temporal and spatial overlap of the two beams were achieved by monitoring the blueshift of the probe pulse wavelength and by imaging the interaction region [15]. The temporal resolution of our pump-probe measurements was less than 1 psec.

Thomson scattered emission near 527 nm was imaged with a narrow bandpass filter onto the 90° camera. When only the probe pulse was injected into the gas jet, very little Thomson scattered emission was observed even though a plasma was created. However, if both pump and probe pulses were incident simultaneously on the gas jet, a bright image of scattered probe light (at 527 nm) was observed in the region closely corresponding to where the pump beam was channeling. This emission is probably caused by the coherent Thomson scattering of the probe laser from the ion acoustic waves generated in the turbulent decay of the large amplitude plasma wakefields [15]. This emission was observed even as the temporal separation between the pump and probe laser pulses were increased by more than the laser pulsewidth (see Figure 2). In fact, the brightness of the Thomson scattered image from the probe reached a maximum approximately 15 psec after passage of the pump pulse. Thomson scattered emission from the probe continued for pump-probe delays of ~50 psec before decreasing significantly.

As the delay between pump and probe pulses is changed the observed waveguide structure also appears to change qualitatively. It is clear from Figure 2 that for small temporal separations the Thomson emission profile of the probe light has a complex structure. However, if the delay is increased by several tens of picoseconds the Thomson scattered image appears

smoother. This effect may be due to hydrodynamic motion of the plasma which may smooth out nonuniformities caused by the channel production mechanism. In addition, as the size of the plasma channel is increased, the decrease in the probe light intensity could also lead to a decrease in the level of Thomson emission. Such motion should occur at approximately the sound speed in the plasma. The plasma temperature from similar interactions has been measured to be about 100 eV [17] which results in a sound speed of about 0.1 μm/ psec whcih aggres with the time scales observed in the Thomson scattered probe light. At large delays the observed emission near 527 nm (see Figure 2 F and G) is second harmonic light generated by the pump laser itself [18, 19].

We have also profiled the exit mode structure of the probe pulse during this interaction by imaging the focal spot with a corrected lens onto a CCD array. These images were obtained by adjusting the position of the array so that the lens imaged the exit of the channel. A profile of the mode structure at the channel exit is displayed in Figure 3. Figure 3 A) shows an image of the focal spot (~ 10 μm) of the probe beam without plasma while Figure B) shows a profile of the probe beam waist at the exit of the high intensity laser-produced channel (about 1.5 mm from the position of best focus shown in Fig 3 A). The exit mode from the channel essentially maintains the original single mode structure with higher order rings surrounding it.

Since the Thomson scattering image of the probe beam is qualitatively similar to that of the pump beam (see Figure 2) it is clear that a waveguide structure is formed in the wake of the high intensity pump pulse. Although the pump pulse may be influenced by relativistic self-focusing, the probe pulse is too weak to impart relativistic quiver velocities to the plasma electrons. The observed channel is also probably not caused by the outward propagation of a high density shock wave which has been used to produce a plasma waveguide in previous experiments [5]. The plasmas created in these experiments should be relatively cold and the creation of a channel of diameter 10 μm using the hydrodynamic evolution of a plasma column should require at least several hundred picoseconds.

The formation of a plasma channel can be most easily attributed to the effects of ponderomotive forces associated with the intense pump laser pulse as it propagates through the plasma. Initially, the pump laser pulses exerts a ponderomotive force on the plasma electrons and expels them radially. This sets up a large space charge force which propels the ions outward from the axis of propagation (a "Coulomb explosion" [2]). After the passage of the pump pulse, the ions continue to drift radially at approximately the ion acoustic speed $C_s = (ZT_e/m_i)^{1/2}$, thus creating a plasma channel, where Z is the number of electrons per ion, T_e (T_i) is the electron (ion) temperature, and m_e (m_i) is the electron (ion) mass. The electron motion is described by the radial force balance, $e\nabla_\perp\phi = m_e c^2\nabla_\perp(1+a^2/2)^{1/2} + n_e^{-1}\nabla_\perp P_e$, where $e\nabla_\perp\phi$ is the space charge force, $m_e c^2\nabla_\perp(1+a^2/2)^{1/2}$ is the ponderomotive force, $P_e = T_e n_e$ is the electron pressure, and n_e is the electron density. This expression neglects the generation of plasmas waves and assumes that the axial length of the laser pulse is large compared to the laser spot size and the plasma wavelength. In the linear regime, the ion motion is described by the continuity equation $\partial\delta n_i/\partial t = -n_{i0}\nabla_\perp \cdot \mathbf{v}_\perp$ and the momentum equation $m_i\partial\delta \mathbf{v}_\perp/\partial t = -Ze\nabla_\perp\phi$, where δn_i and n_{i0} are the perturbed and ambient ion densities, $\mathbf{v}_\perp$ is the radial ion velocity, and $T_i << T_e$ is assumed. Combining the electron radial force balance, the ion continuity equation, and the ion momentum equation yields

$$\left(\frac{\partial^2}{\partial t^2} - C_s^2\nabla_\perp^2\right)\frac{\delta n_i}{n_{i0}} \cong \frac{Zm_e}{4m_i}\nabla_\perp^2 a^2 \tag{1}$$

assuming $\delta n_i^2 / n_{i0}^2 << 1$, $a^2 << 1$, and an isothermal equation of state. Equation (1) is similar to that used to describe stimulated Brillouin scattering [20].

Using the 2D Green's function for the wave equation, the solution to Eq. (1) is given by

$$\frac{\delta n_i}{n_{i0}} = \frac{Zm_e}{8\pi\beta_s m_i}\int_{-\infty}^{\infty} d\zeta' \int_{-\infty}^{\infty} dx' \int_{-\infty}^{\infty} dy' \frac{\nabla_\perp'^2 a^2(\zeta', \mathbf{r}')}{\left[\beta_s^2(\zeta-\zeta')^2 - |\mathbf{r}-\mathbf{r}'|^2\right]^{1/2}} \tag{2}$$

where $\beta_s = C_s/c$, $\zeta = z - ct$, $\mathbf{r} = x\mathbf{e}_x + y\mathbf{e}_y$, and the integrand is only non zero in the region $\beta_s(\zeta-\zeta') > |\mathbf{r}-\mathbf{r}'|$. Equation (2) has been evaluated for a non evolving laser pulse of the form $a^2 = a_0^2 f(\zeta) exp\left(-2r^2/r_0^2\right)$, with $f = \sin^2(\pi\zeta/L)$ for $0 \le \zeta \le L$ and $f = 0$ otherwise. The evolution

of the density channel is shown in Fig. 4 for the parameters $a_0 = 0.25$, $r_0 = 10$ μm, L = 120 μm, $T_e = 100$ eV, Z = 2, $m_i/m_e = 7300$, and $\beta_s = 2.3 \times 10^{-4}$. Analysis indicates that the density channel reaches a maximum depth of $\delta n_{i0}/n_{i0} \cong -\alpha_1(Zm_e/\beta_s m_i)a_0^2 L/r_0$ after a distance of $\zeta_c = \alpha_2 r_0/\beta_s$, where $\alpha_{1,2}$ are constants which depend on the shape of the laser pulse profile (for the example in Fig. 4, α_1~0.?, α_2~0.?). For $\zeta^2 << \zeta_c^2$, the channel depth increases roughly linearly, $\delta n_i / n_{i0} \cong \alpha_3(\zeta/\zeta_c)\delta n_{i0}/n_{i0}$, and for $\zeta^2 >> \zeta_c^2$, the channel depth decreases roughly as $\delta n_i / n_{i0} \cong \alpha_4(\zeta_c/\zeta)\delta n_{i0}/n_{i0}$, where $\alpha_{3,4}$ are constants. Fig. 4 indicates a maximum density depletion is reached at ~30 psec for the simulation parameters. Despite the simplifying assumptions used, these calculations clearly show evidence that a short lived plasma channel can be created in the wake of a high intensity laser propagating through underdense plasma — agreeing qualitatively with experimental results .

In conclusion, we have shown that a plasma channel can be created immediately behind a high intensity laser pulse as it propagates through a gas jet plasma. The formation of this channel is consistent with the expulsion of both electrons and ions from the path of the laser via ponderomotive effects. This is the first measurement of such channels over the temporal duration of ~50 psec where they can be maintained. This phenomena may be useful for laser driven high energy electron accelerator applications, x-ray laser, or laser fusion experiments.

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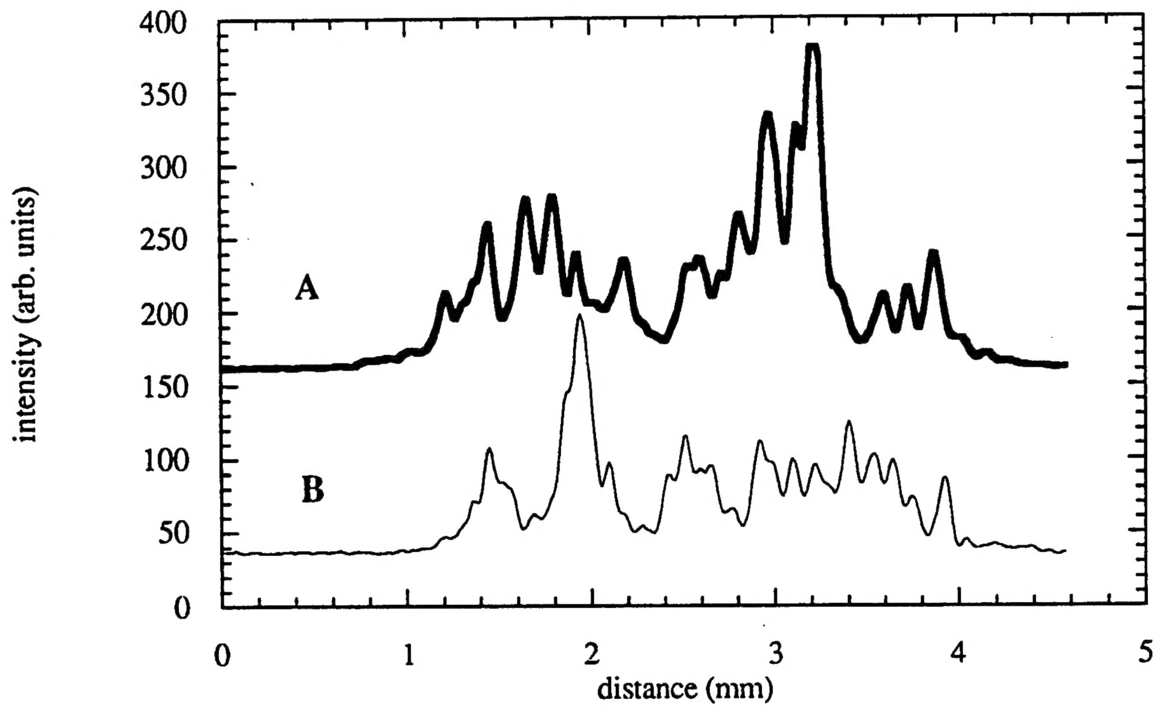
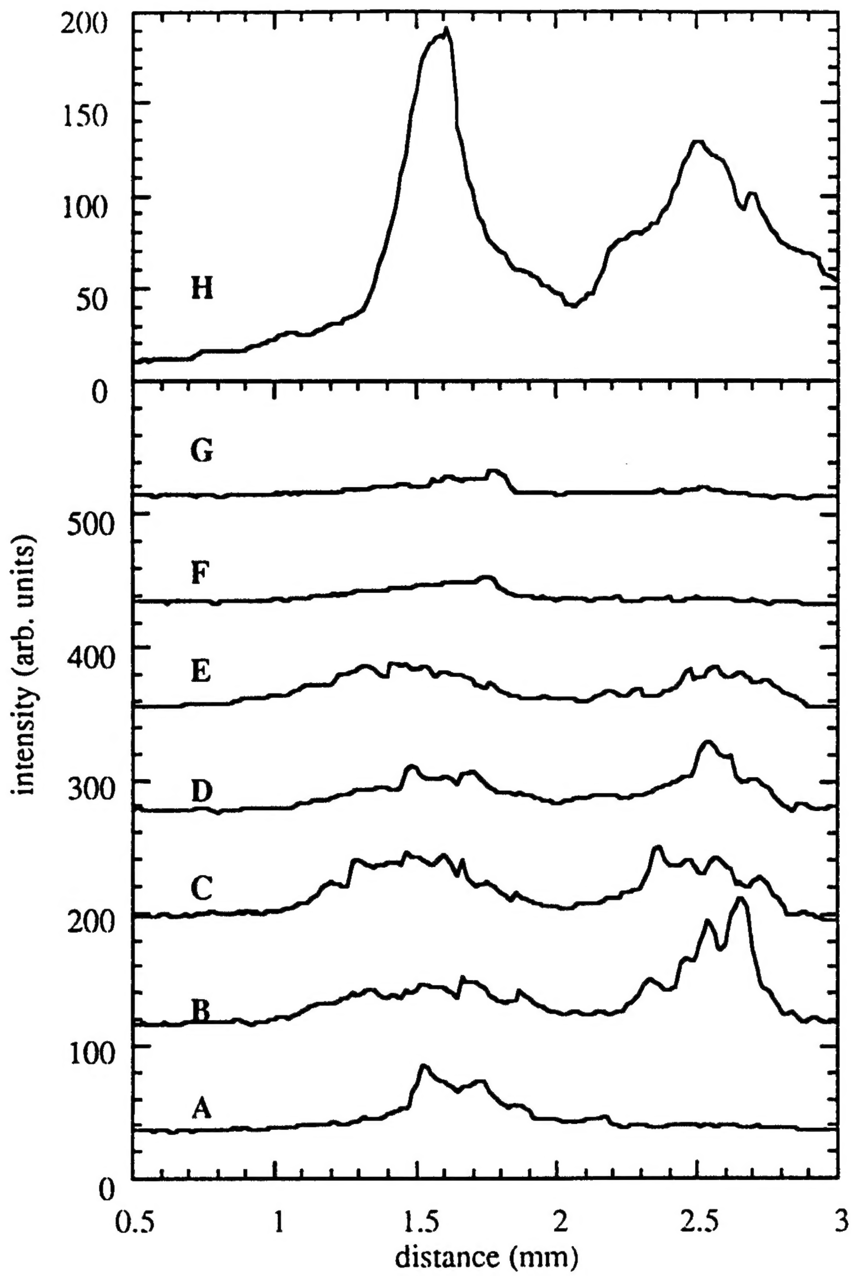


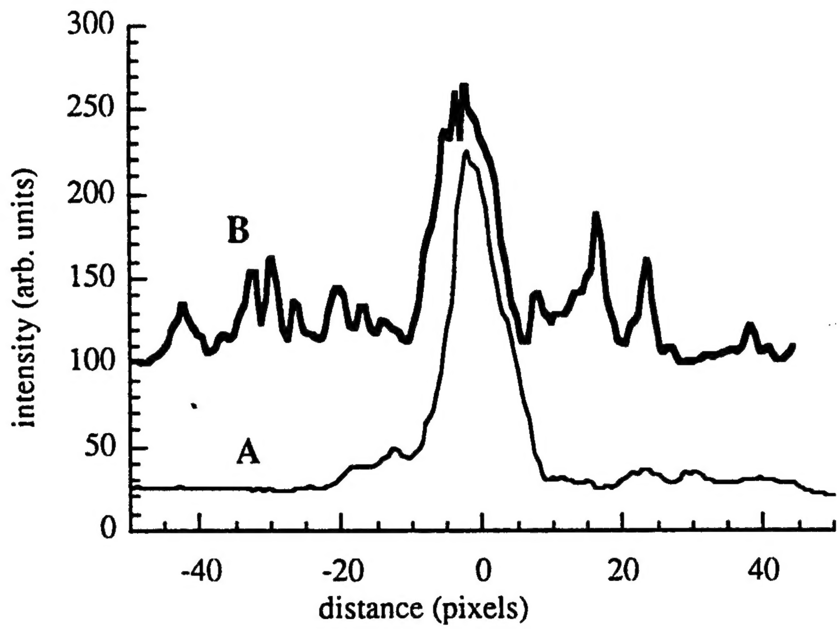
[Fig. 1] CCD image of Thomson scattered emission of the pump beam in a hydrogen gas jet for A) 2 TW, B) 1 TW



[Fig. 2] Thomson scattering images of interaction of picosecond probe beam (527 nm) for various delay settings between pump and probe beam in hydrogen gas jet.

A) 0, B) 6, C) 14, D) 22 E) 30, F) 46, G) 62 psec

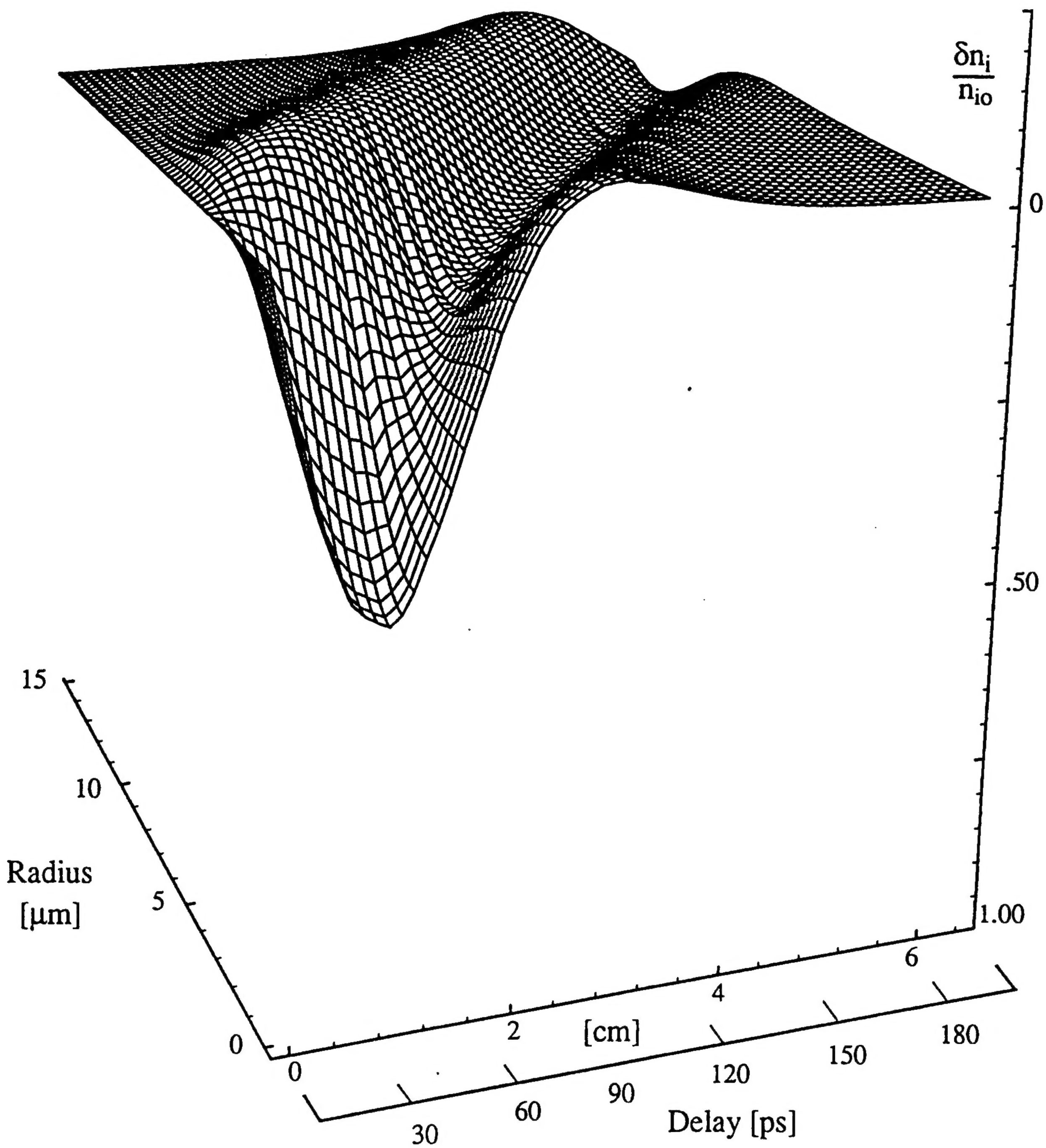
H) Thomson scattered emission near 1.054 μm from pump beam (2 TW) for similar experimental conditions as A) - G).



[Fig. 3] Profiles of focal spot images

A) focal spot profile of probe beam without plasma (FWHM diameter is ~ 5 μm)

B) exit mode profile of probe beam waist at channel exit for delay setting between pump and probe beam of 75 psec.



[Fig. 4] Solution of Equation 2 for parameters discussed in text. A region of plasma density depletion is produced approximately 30 psec after passage of the high intensity pulse.